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Vertical zoning and differentiation in granitic rocks---central Flint Creek Range Montana

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VERTICAL ZONING AND DIFFERENTIATION IN GRANITIC ROCKS -- CENTRAL FLINT CREEK RANGE, MONTANA

by

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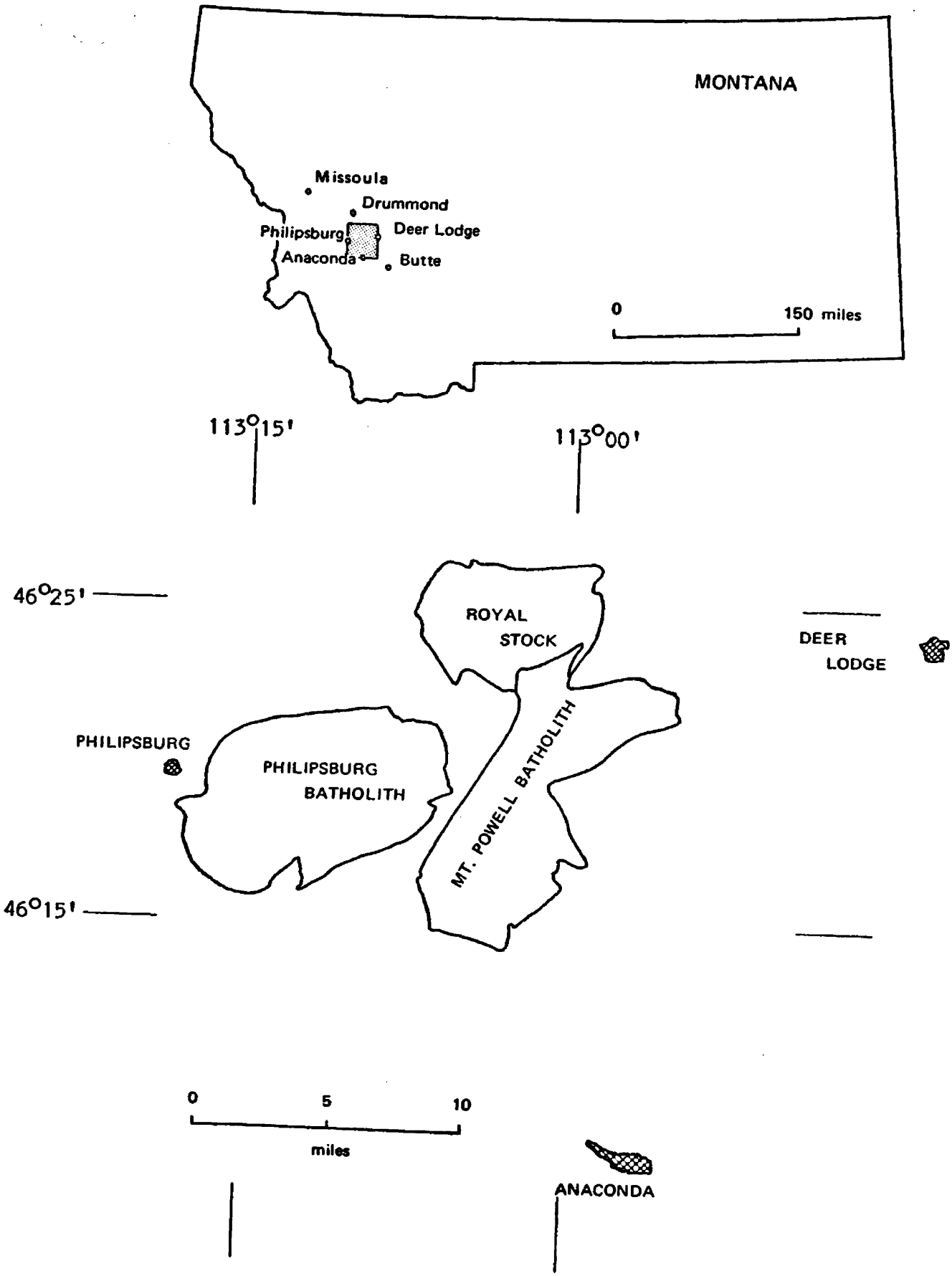
INTRODUCTION

Many concentrically zoned granitic plutons which grade from relatively mafic margins into more felsic cores have been described (Compton, 1955; Taubeneck, 1957; Reesor, 1958; Bateman and others, 1963; Ehinger, 1971, 1972). This zoning is believed by some workers to have originated by assimilation of country rock near the margins of the pluton (Compton, 1955; Reesor, 1958). Vance (1961), however, has suggested a model involving differentiation in place to explain the detailed zoning in some such plutons. In Vance's model, a magma differentiating in place develops an impermeable shell which forces the sealed-in volatiles, along with silica and alkalis, to migrate downward and inward as the shell thickens. The interior and deeper portions of the magma are enriched in these components while a more mafic shell is left behind.

Most previous studies of zoned granitic plutons have dealt only with horizontal (visible in plan view) chemical or mineralogical zoning although similar vertical (visible in cross-sectional view) zoning should also be produced during differentiation in place. Structural data combined with the presence of vertical, and apparent absence of horizontal, chemical zoning suggests that what is now the Royal stock of west central Montana represents the uppermost shell of a zoned pluton which has differentiated in place. Chemical, structural, and age relationships between the Royal stock and the closely associated Mount Powell batholith (Fig. 1) suggest that the Mount

FIGURE 1 LOCATION MAP — FLINT CREEK RANGE



Powell batholith was originally the more felsic deeper portion of the differentiating Royal stock magma. This deeper portion, while still in a molten state, broke through the outer solidified shell and now appears as a separate pluton.

Regional Geology

The Royal stock and Mount Powell batholith, along with the concentrically zoned Philipsburg batholith (Ehinger, 1971, 1972), form the higher portions of the Flint Creek Range in west central Montana (Fig. 1). No widespread regional metamorphism has affected this area which lies between the Idaho and Boulder batholiths. The surrounding sedimentary rocks range from Precambrian to Tertiary in age. McMannis (1965) has placed the Flint Creek Range in the Batholithic Province of Montana. This province contains many large and small plutonic bodies, a thick Belt sequence, many Cretaceous and Cenozoic volcanic rocks, and has an exceedingly complex structure (McMannis 1965).

Previous Work

Emmons and Calkins (1913) were the first to map a large part of the Flint Creek Range. The northeastern and northwestern flanks of the range have been studied in more detail since then by Mutch (1960) and McGill (1958). Allen (1962, 1966) has studied the structure and petrology of the Royal stock and Mount Powell batholith.

Work in Progress

Work currently in progress in the area consists of a study of feldspars from the Philipsburg batholith by Ronald Wold and a fission track study of the Royal stock and Mount Powell and Philipsburg batholiths by Bruce Baty as part of a large-scale project involving the plutons of the Flint Creek Range by Dr. Donald W. Hyndman and Dr. Arnold J. Silverman of

the University of Montana.

Purpose and Methods

The purpose of this study is to investigate the relationships between the Royal stock and Mount Powell batholith by the use of structural, chemical, and rock density data.

A line of 18 samples, collected for the above project, running from north to south through the Royal stock and the northern portion of the Mount Powell batholith, and seven additional samples taken from the middle and southern part of the batholith (Fig. 2) were selected for whole rock chemical analyses. Twenty-three biotite separates from the line of samples were also chemically analyzed. Vertical chemical variation in the plutons along the line of samples is the subject of much of this paper. Modal analyses and magnetic susceptibility data were also gathered for some of the samples. Specific gravities of numerous samples from both plutons were measured as a part of the larger project using the technique described by Ehinger (1971). From this rock density data Dr. Donald Hyndman prepared the rock density map shown in Fig. 6.

General Features of the Royal Stock and Mount Powell Batholith

The Royal stock is an oval body covering 30 square miles. Mineralogically it is quite homogeneous (Allen, 1962) and according to the classification of Streckeisen (1967) it is a granodiorite. In hand specimen the Royal stock has a normal granitic texture (hypidiomorphic granular), with the exception of finer-grained margins which appear gneissic due to a foliation imparted by the biotite.

The Mount Powell batholith, covering 53 square miles, is south of the Royal stock and in contact with it. In hand specimen it is distinguished from the Royal stock by the presence of muscovite and/or large potassium

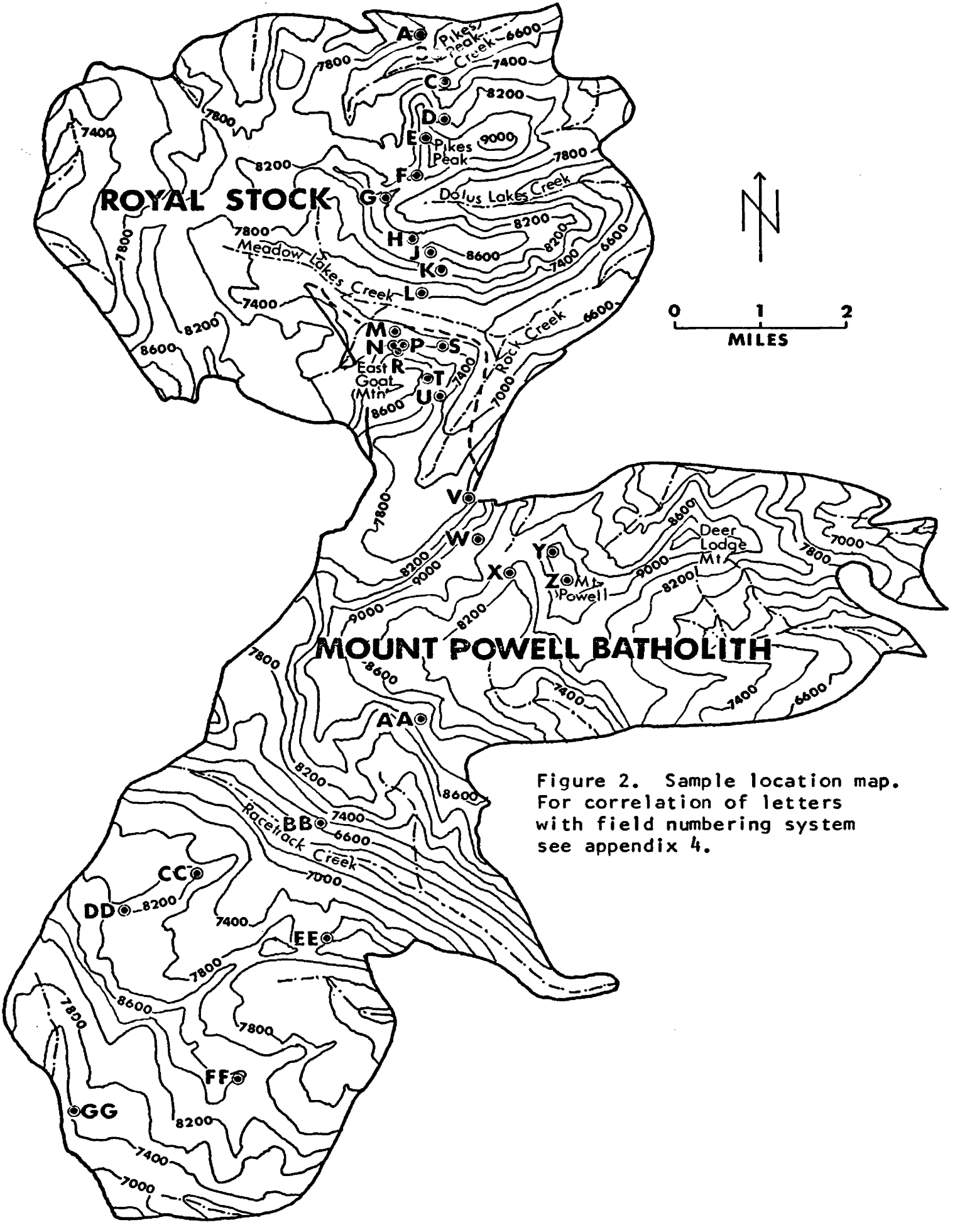


Figure 2. Sample location map. For correlation of letters with field numbering system see appendix 4.

feldspar megacrysts which constitute up to 50% of the outcrop in some small areas. Aside from this, both plutons are texturally similar although foliation in the Mount Powell batholith is rare. Mineralogically the groundmass of the Mount Powell batholith is also classified as a granodiorite, but if the megacrysts are considered the batholith is probably a granite (Streckeisen classification 1967). Neither pluton shows concentric mineralogical zoning. Aplite dikes are present in both plutons, but the joint systems in each pluton are different (Allen, 1962). The contact between the two plutons ranges from gradational far from the country rock, to very sharp near the country rock contacts. The country rock contacts are everywhere sharp and a contact metamorphic aureole surrounds both plutons. Hornblende hornfels facies rocks are found next to the contact with albite-epidote facies rocks farther away (McGill, 1958: Mutch, 1960; Allen, 1962).

The Royal stock and Mount Powell batholith are probably closely related in time of emplacement and subsequent thermal history to the nearby Philipsburg batholith for which K/Ar ages of 72 to 76 million years have been obtained (Hyndman, Obradovitch, and Ehinger, 1972).

Chapter 2

MINERALOGY AND MODAL ANALYSES

The mineralogy of the Royal stock and Mount Powell batholith is that of a normal biotite granodiorite and has been described in detail by McGill (1958) and Allen (1962, 1966).

Mineralogically, both plutons are very similar. Zoned plagioclase, generally ranging from An_{31} to An_{35} in the Royal stock and from An_{27} to An_{30} in the Mount Powell batholith (Allen, 1962), is the most abundant mineral. It is followed by quartz, potassium feldspar, and biotite in decreasing order of abundance (Table 1). Potassium feldspar megacrysts which are usually randomly oriented, up to three inches long, and contain many inclusions of plagioclase are common in the Mount Powell batholith. Much smaller, anhedral megacrysts are rarely present in the Royal stock.

Accessory minerals include magnetite, apatite, zircon, and monazite. Chlorite, epidote, rutile, and muscovite are secondary minerals. Biotite and muscovite will be discussed in more detail in the section on biotite chemistry (Chapter 7).

Modal analyses (Table 1) of stained slabs and thin sections performed by the writer (Appendix 1) are in agreement with those of Allen (1962) and Hyndman and Silverman (unpublished data) which show the Mount Powell batholith to be enriched in quartz, potassium feldspar, and muscovite and depleted in mafics and plagioclase relative to the Royal stock. This data, combined with the lower An contents of plagioclase in the Mount Powell

Table 1

Modal analyses of 11 Royal stock samples

(2000 counts per stained slab and 1440 counts per thin section)

	Stained Slabs				Thin Section	
Sample	Plag.	K-spar	Quartz	Mafics	Biotite	Muscovite
A	43.5	19.5	23.9	13.0	8.8	1.3
B	44.8	15.7	25.7	14.7	5.1	.9
C	43.3	15.8	29.6	11.3	6.8	2.2
D	44.3	13.4	23.9	18.4	10.9	.8
E	42.5	18.1	28.8	10.5	6.9	.9
F	45.6	21.0	19.8	13.5	6.5	2.0
G	40.0	18.8	23.6	17.6	7.3	1.9
H	44.4	22.7	18.9	14.0	10.5	2.2
J	44.8	18.1	24.0	14.0	6.3	3.2
K	44.0	18.6	27.7	9.8	6.5	1.4
L	45.5	20.9	24.3	9.3	8.3	.6
Average	43.8	18.3	24.6	13.3	7.6	1.6
Allen (1962): 30 samples						
Average	47.4	16.9	26.7	9.0		
Hyndman-Silverman (unpublished data): 118 samples						
Average	45.0	17.8	26.6	10.9		

Modal analyses of 9 Mount Powell batholith samples

	Stained Slabs				Thin Section	
Sample	Plag.	K-spar	Quartz	Mafics	Biotite	Muscovite
N	46.6	18.1	27.4	7.8	3.4	2.1
R	40.1	25.0	29.1	5.8	3.1	3.4
P	50.1	16.8	22.5	10.6	3.5	6.0
T	44.2	20.5	27.7	7.6	4.2	4.5
V	46.8	14.5	27.4	11.3	4.9	5.4
W	44.0	20.8	26.4	9.0	7.1	5.1
X	49.0	18.8	26.6	5.8	1.9	3.8
Y	40.4	22.6	32.9	4.2	1.0	7.6
Z	37.9	31.3	22.9	7.9	1.2	2.5
Average	44.3	20.9	27.0	7.8	3.2	4.5
Allen (1962): 32 samples						
Average	46.9	18.0	28.8	6.1		
Hyndman-Silverman (unpublished data) :201 samples						
Average	42.3	22.4	28.5	7.2		

*The total biotite plus muscovite contents from the thin sections rarely equal the mafic contents obtained from the stained slabs. This is partly because opaques and accessory minerals were not counted with biotite or muscovite in thin section. The small size of the thin section is probably not representative of the sample and the small size of the mafic minerals in the stained slabs probably also introduces additional errors.

batholith and the gradational contacts between the two plutons suggests both plutons are comagmatic, the Mount Powell batholith being a differentiate of the original Royal stock magma.

The modal analyses show no mineralogical zoning in the Royal stock or Mount Powell batholith. Because of the presence of numerous, irregularly-distributed megacrysts in the Mount Powell batholith, some of the stained slabs from this pluton were unsuitable for point counting. It is believed the modal analyses of the Mount Powell batholith therefore are suspect and should be used only for general observations.

Chapter 3

STRUCTURE

The Royal stock has been classified as an epizonal pluton (Buddington, 1959) by Mutch and McGill (1962) on the following evidence: contacts with the country rock are sharp, primary platy flow structure is well developed only near the margins of the pluton, the stratigraphic thickness overlying the stock during intrusion is estimated as 17,000 feet, and metamorphism developed in association with the Royal stock is commonly of the albite-epidote hornfels facies. Except for the rarity of platy flow structure near the country rock contact, the Mount Powell batholith is very similar to the Royal stock.

Intrusion of the Royal stock (Mutch and McGill, 1962) and the Mount Powell batholith has deflected pre-existing regional structures. The regional north-south structural trends in the country rock swing abruptly and concordantly around both plutons (Fig. 3). In detail, however, the plutons are strongly discordant, often cutting across bedding at high angles. It is believed that stoping was unimportant as a mechanism of emplacement, as xenoliths are very rare in the Royal stock and absent in the Mount Powell batholith. Both plutons contain large sedimentary roof remnants which are located near the igneous-country rock contact or at high elevations. These roof remnants appear to be in their original position and thus are useful in estimating the original position of the roofs of these bodies.

Foliation developed most strongly near the margins of the Royal stock and an absence of shearing in both plutons (Mutch and McGill, 1962; Allen,

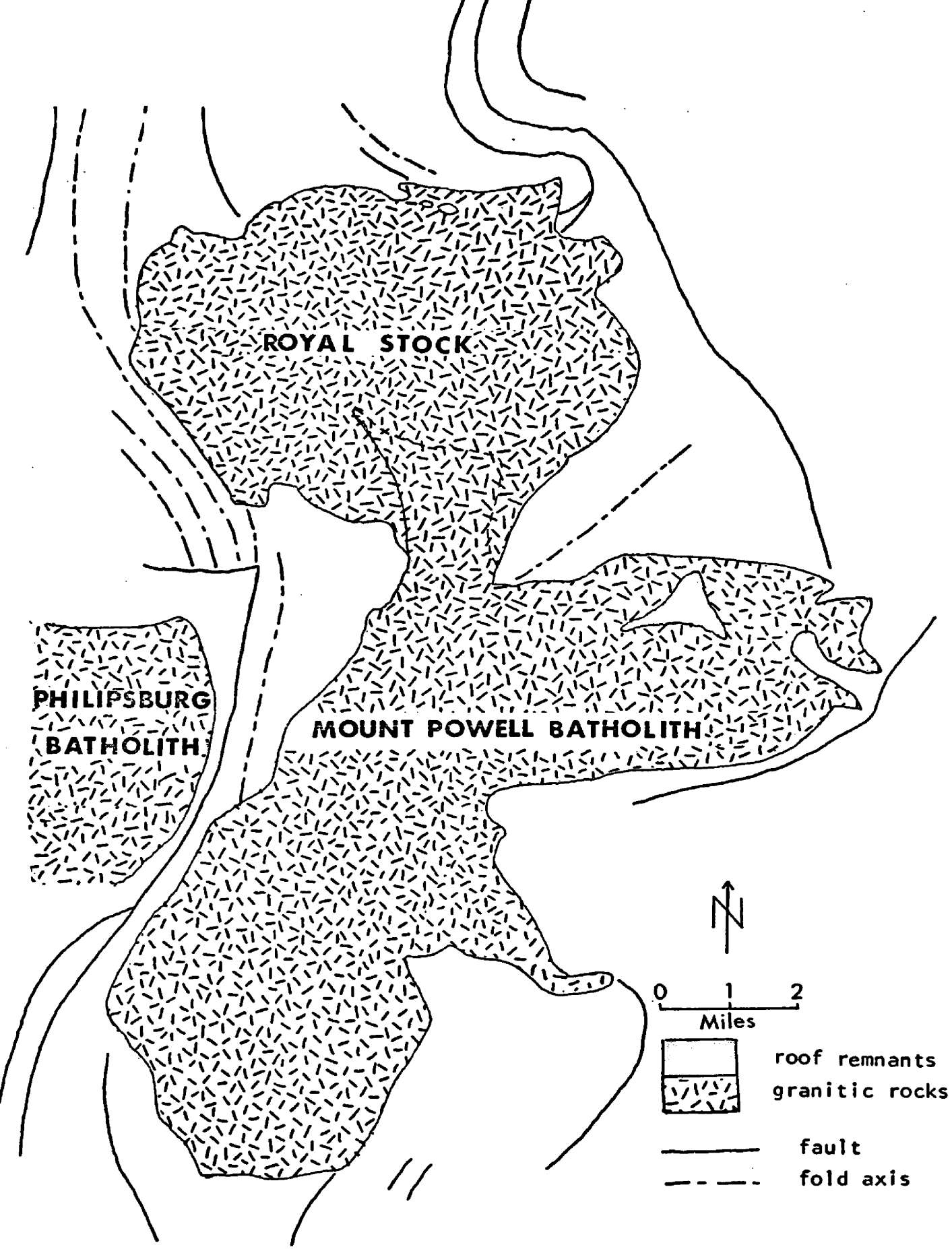


Figure 3. General relations between the Royal stock and Mount Powell batholith and the deflected country rock structure. Geology compiled from McGill (1958), Mutch (1960), Allen (1962), and Winegar (1970).

1962) suggests intrusion of a fluid magma. Granitic dikes invading the country rock are also indicative of a fluid magma (Allen, 1962). It is believed both plutons were forcibly injected in a fluid state.

Allen (1966) has proposed that the Royal stock is a prismatic-cylindrical body plunging about 55° to the southwest. This is based on what are interpreted to be extension fracture orientations. McGill (1958), however, believes intrusion to be from the east and controlled in part by folds in the country rock. Evidence for this is the presence of east dipping axial planes, and a steep western and shallower eastern dip of the pluton-country rock contact. As the shallow dip of the eastern contact may represent incomplete deroofing, with still steeper dips still unexposed (Figs. 4 and 5), Allen's interpretation of intrusion from the southwest is preferred.

Wherever a foliation in the Royal stock is found near the margins, it is oriented parallel to the contact. Therefore it seems reasonable to extrapolate the attitude of the contact from the attitude of the foliation where the contact is not exposed (Allen, 1962). Observed foliations in the Royal stock are shown in Figure 4. Cross sections, based upon foliation orientations, the location of roof remnants, and the dips of contacts (Fig. 5) suggest that the original roof of the Royal stock and northern portion of the Mount Powell batholith was generally only several hundred feet above the higher ridges and quite flat. It is also evident that the Mount Powell batholith partially underlies the Royal stock.

Mutch (1960) has noted shearing and alteration of the Royal stock south of Rock Creek where it is in contact with fresh rock of the Mount Powell batholith. This suggests the Mount Powell batholith has intruded the Royal stock. Allen (1962) has reported the Mount Powell batholith cuts across the foliation of the Royal stock. This is also in agreement with the Mount Powell batholith being the younger of the two bodies.

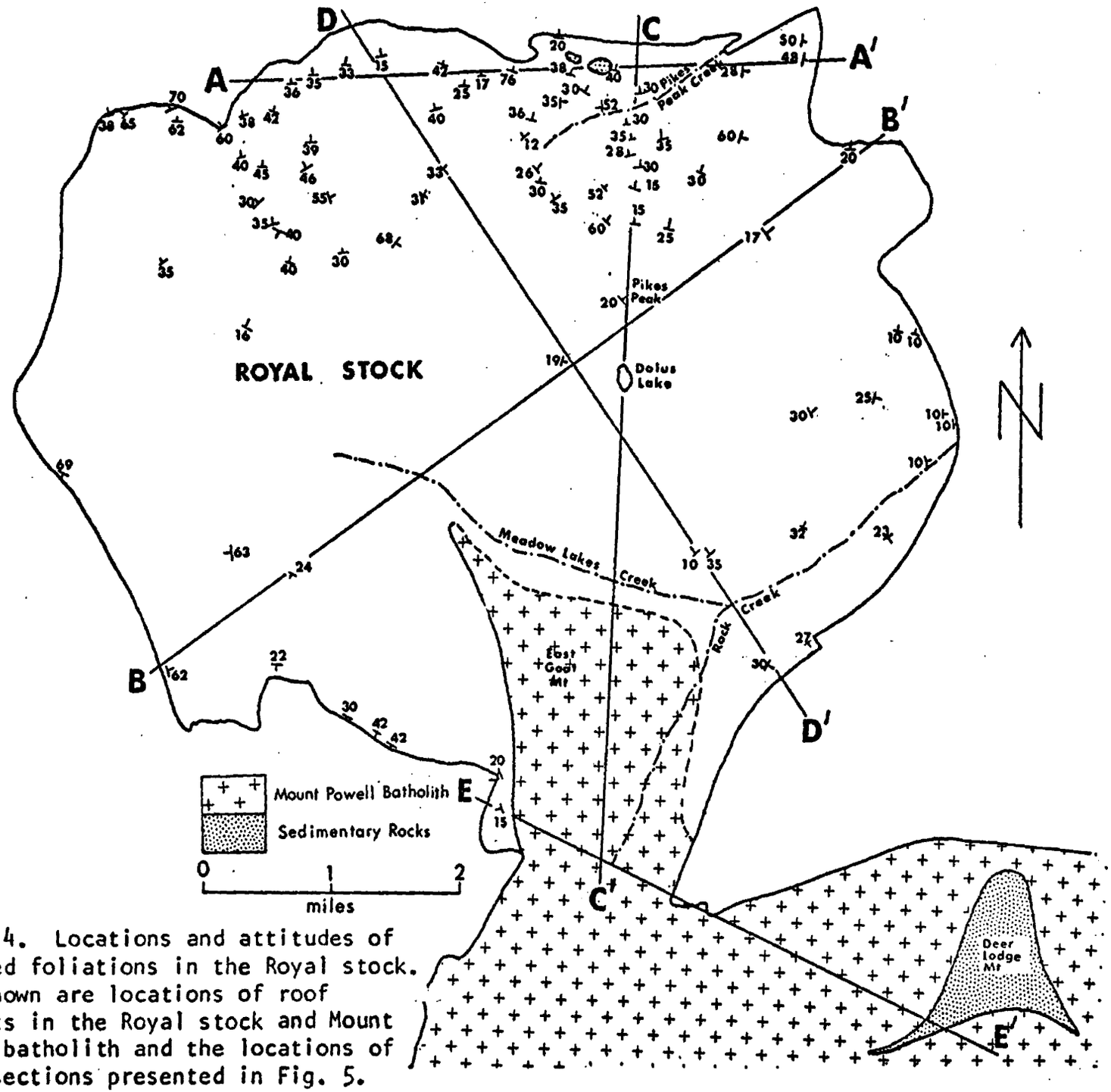


Figure 4. Locations and attitudes of observed foliations in the Royal stock. Also shown are locations of roof remnants in the Royal stock and Mount Powell batholith and the locations of cross sections presented in Fig. 5.

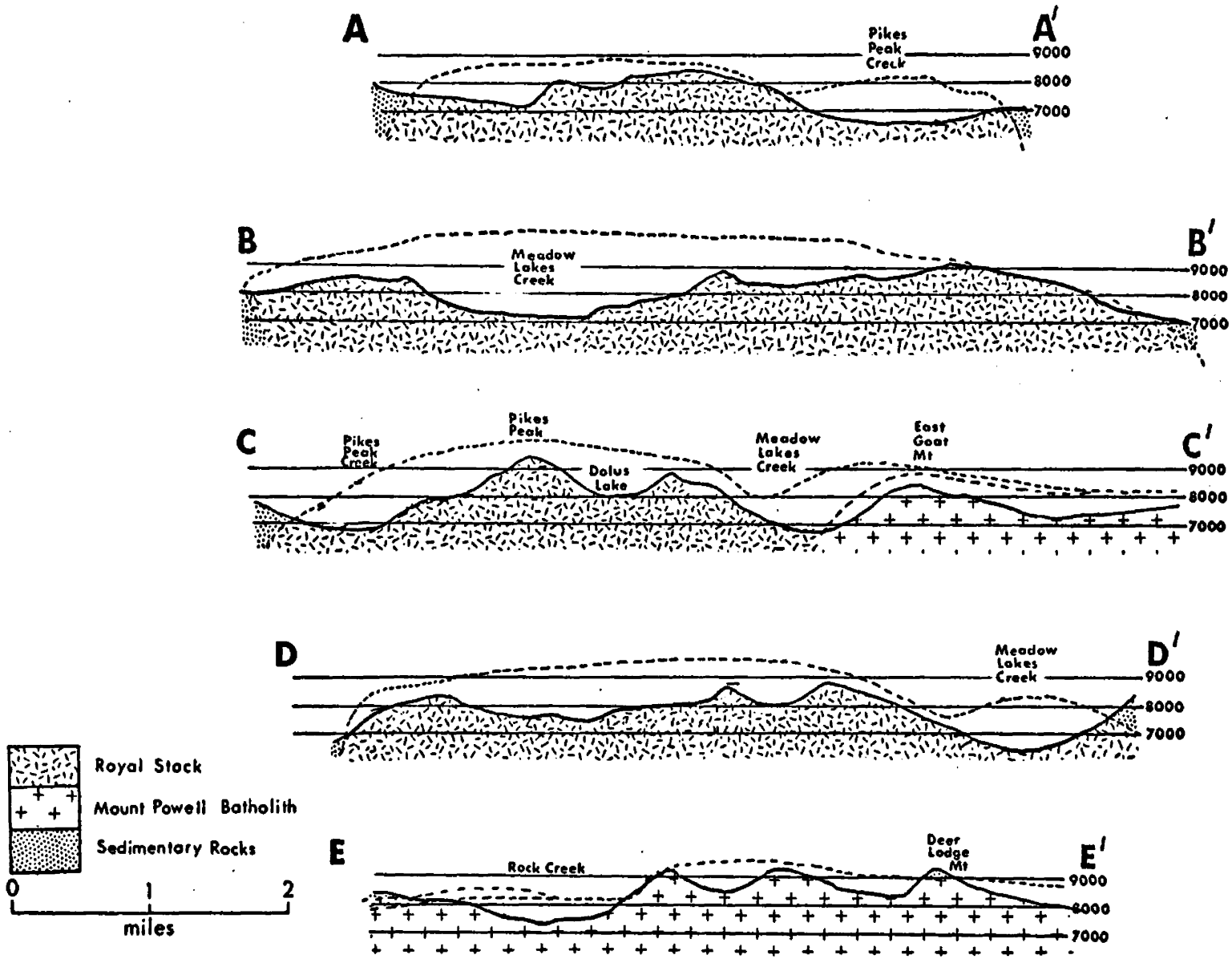


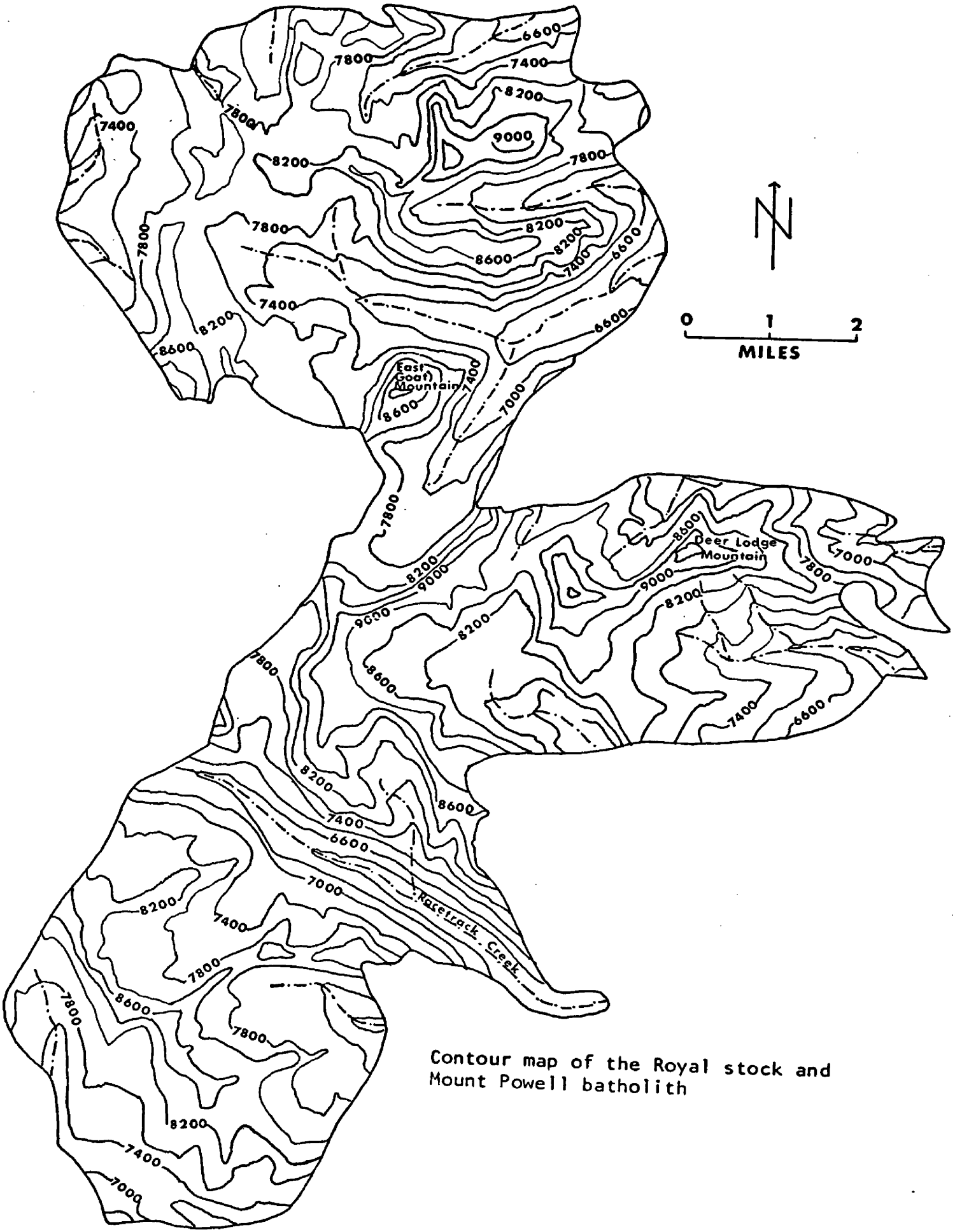
Figure 5. Estimated position of the original roof of the Royal stock and northern Mount Powell batholith based on foliation orientations, dips of igneous-country rock contacts, and roof remnant locations. Locations of the cross sections are shown in Fig. 4. Estimated roof is shown by the dashed lines.

Chapter 4

ROCK DENSITY

A density map of the Royal stock and Mount Powell batholith (Fig. 6), contoured by D. W. Hyndman to demonstrate a correlation between density and elevation, shows the density of the Royal stock to be greatest near the border zones and higher elevations. The density ranges from 2.67 to 2.69 for the border zones and higher elevations to 2.60 to 2.63 for the central valleys. This density distribution suggests the exposed portion of the Royal stock may represent the upper part of a mafic shell surrounding a zoned pluton. This is in agreement with the structural cross sections (Fig. 5) which show the original roof of the Royal stock to be only several hundred feet above the higher ridges. The modal analyses of the Royal stock, however, do not readily show mineralogical zoning.

In the Mount Powell batholith, rock densities generally range from 2.61 to 2.65 and show little if any correlation of higher values with the border zones. However, higher values do seem to correlate with increasing elevation in the northern part of the Mount Powell batholith (e.g. Deer Lodge and East Goat Mountains) suggesting more mafic rock is associated with the roof of the batholith (Fig. 5). In the southern part of the batholith in the Racetrack Creek Valley the density increases with decreasing elevation possibly suggesting erosional levels close to a more mafic floor of the batholith. Areas between Deer Lodge Mountain and Racetrack Creek have lower densities which suggest this area of intermediate elevation may represent



Contour map of the Royal stock and Mount Powell batholith

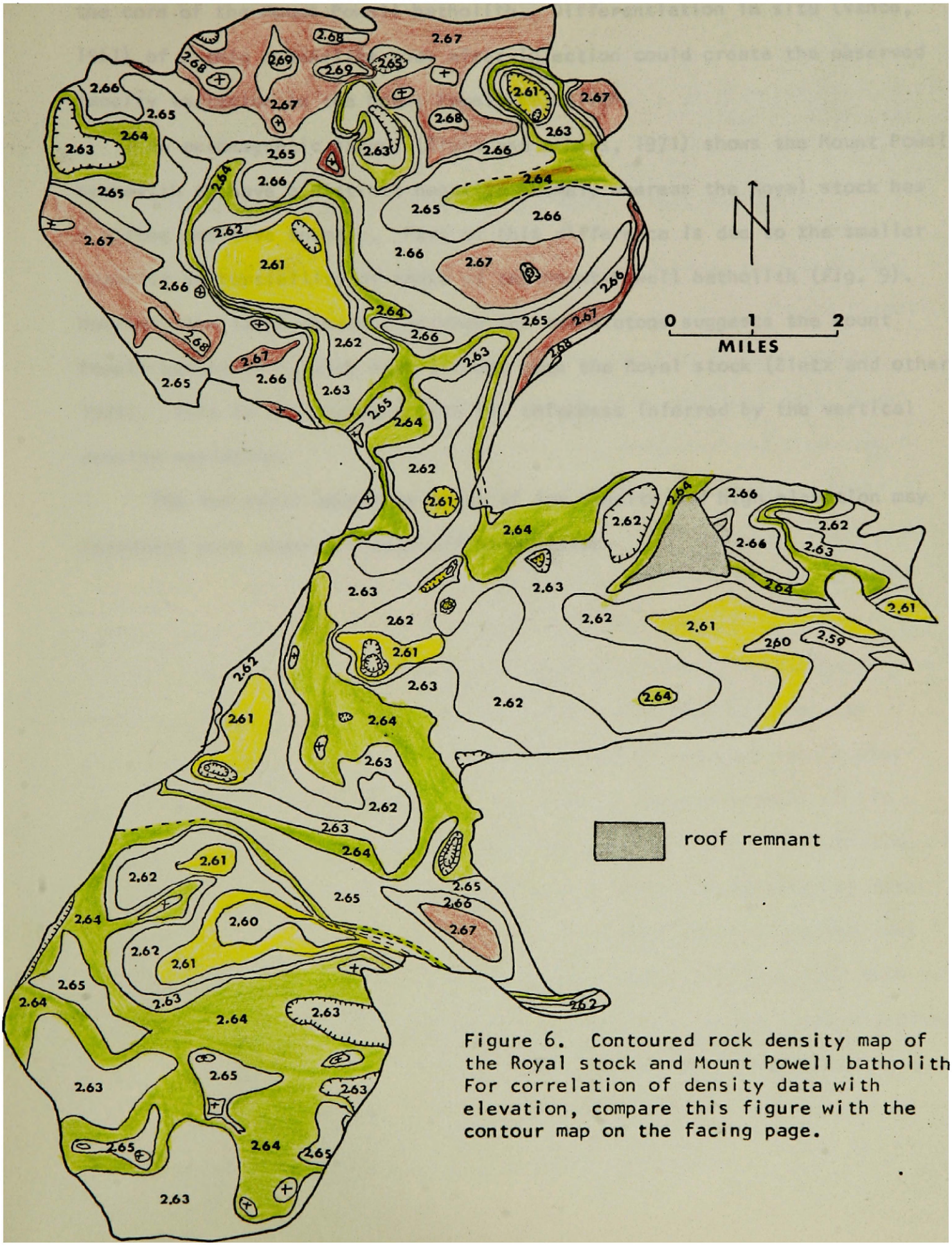


Figure 6. Contoured rock density map of the Royal stock and Mount Powell batholith. For correlation of density data with elevation, compare this figure with the contour map on the facing page.

the core of the Mount Powell batholith. Differentiation in situ (Vance, 1961) of a thin sheet-like body after injection could create the observed density variation in the Mount Powell batholith.

An aeromagnetic survey (Zietz and others, 1971) shows the Mount Powell batholith to have a distinct negative anomaly whereas the Royal stock has a strong positive anomaly. Part of this difference is due to the smaller magnetic susceptibility of rocks of the Mount Powell batholith (Fig. 9). However, the large contrast between the two plutons suggests the Mount Powell batholith is also much thinner than the Royal stock (Zietz and others, 1971). This is in agreement with the thickness inferred by the vertical density variation.

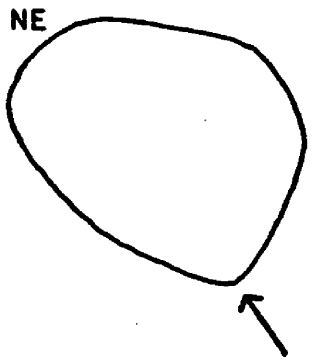
The few small anomalous areas of low density and high elevation may represent more advanced local differentiation.

Chapter 5

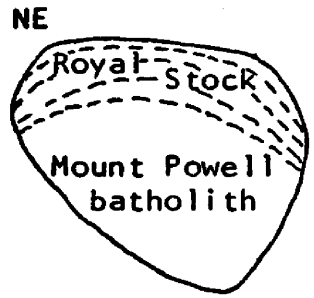
DEVELOPMENT OF THE ROYAL STOCK AND MOUNT POWELL BATHOLITH

To account for the observed field, structural, age, mineralogical, and density relationships between the Royal stock and Mount Powell batholith an origin based on interruption of the differentiation in situ process (Vance, 1961) is presented. Whole rock and biotite chemical data, along with magnetic susceptibility measurements, are presented and discussed in the next two chapters and used as additional evidence for the proposed origin.

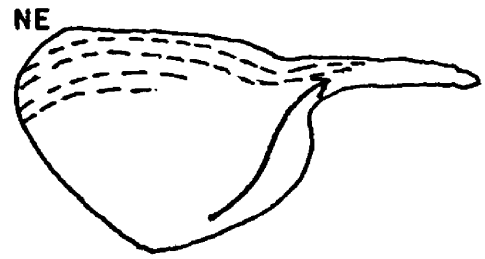
It is proposed that both plutons originated from a single mass of granitic magma which probably rose toward the northeast. The ultimate origin of the magma is outside the scope of this paper. As the magma rose the top and sides would presumably be the first to cool and begin to crystallize, resulting in rocks enriched in mafics and more calcic plagioclase. Continued upward movement would cause the development of the observed flow foliations. Further cooling could result in the formation of a solid impermeable shell which would seal in volatiles released by later crystallization of the remaining magma. The volatiles would gather just below the top of the shell, where the pressure would be least, and then be forced downward and inward as the shell thickened, carrying along dissolved silica and alkalis. It is this selective transfer of silica and alkalis which is considered responsible for the mafic margins of some zoned plutons which grade into more felsic cores (Vance, 1961).



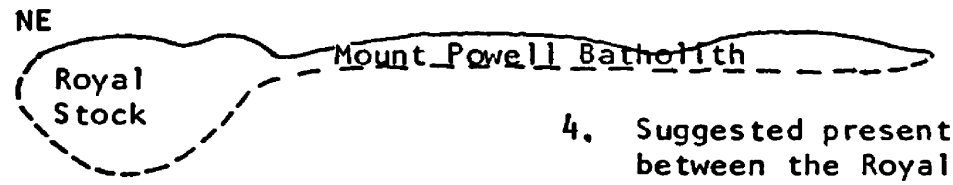
1. Initial Royal stock magma rising toward the northeast at an inclination of 50° or 60°.



2. Cooling of the margins with differentiation taking place to form the Royal stock. Dashed lines represent possible isotherms.



3. Upward movement of the molten core of the Royal stock magma and its injection as a sheet to form the Mount Powell batholith.



4. Suggested present relationship between the Royal stock and the Mount Powell batholith.

Figure 7. Suggested origin of the Royal stock and Mount Powell batholith shown in cross-sectional view along a NE-SW line. Although the figure is not drawn to an absolute scale, the relative proportions are correct.

What is now exposed as the Royal stock probably represents the upper portion of the more mafic margins developed around a zoned pluton. The Royal stock has not yet been eroded far enough below its original roof to reveal a more pronounced horizontal (visible in plan view) concentric compositional zoning which probably would exist given deeper erosion. This is supported by the density and whole rock chemical data (Fig. 9) which show vertical chemical zonation to be present as may be expected for the top of a pluton which has differentiated in place.

Before the Royal stock completely solidified, the deeper, more differentiated, and still mostly molten core of the pluton, perhaps due to gravitational instability, broke through the southern side of the solidified shell and floated to approximately the same level in the crust as the Royal stock (Fig. 7). This more differentiated portion of the magma is now recognized as the Mount Powell batholith. Somewhat similar occurrences of intrusion of the solidified margins of zoned plutons by the still molten core or deeper portions have been reported (Reesor, 1958; Bateman and others, 1963).

In accordance with this proposed origin the Mount Powell batholith partially underlies, locally intrudes and is slightly younger than the Royal stock. Both sharp and gradational contacts between the plutons, different joint sets, and mineralogical and specific gravity distributions are also as expected.

Chapter 6

WHOLE ROCK CHEMISTRY

Chemical analyses of whole rock samples were done using wet chemical, x-ray fluorescence, and flame photometer techniques (Appendix 2). Sample locations are shown in Figure 2.

Whole rock chemical analyses (Table 2) and the associated variation diagrams (Fig. 8) show the Royal stock and Mount Powell batholith each to be internally quite homogeneous and for the most part chemically distinct from the other. However, three samples taken near the contact between the two plutons (N, T, and U) suggest the existence of a gradational relationship. Magnetic susceptibility measurements (Fig. 9), which reflect magnetite content in granitic rocks (Dobrin, 1960), are in agreement with a gradational relationship existing between the two plutons.

With increasing SiO_2 content of samples taken from both bodies, FeO, Fe_2O_3, TiO_2, MgO, CaO, and Al_2O_3 decrease, Na_2O remains constant, and K_2O increases slightly (Fig. 8). The values for samples from the two bodies plot at opposite ends of the variation diagrams (Fig. 8), but the trends and values are such that a transitional relationship between the two bodies is apparent. The variation diagrams for Na_2O and K_2O (Fig. 8) show considerably greater scatter outside experimental error than other elements. This may reflect the presence of the large, irregularly-spaced megacrysts in the Mount Powell batholith which make adequate sampling in the field difficult, if not impossible.

Table 2. Whole rock chemical analyses

	Royal stock							Northern Mount Powell batholith									
Sample	A	C	D	E	G	H	J	K	N	R	S	T	U	V	W	X	Y	Z
SiO_2	66.4	68.1	67.6	67.2	67.9	69.2	67.2	67.1	71.2	73.0	72.8	70.7	69.8	72.3	72.5	73.1	75.3	73.2
TiO_2	.42	.33	.39	.39	.27	.28	.34	.31	.21	.15	.20	.21	.24	.18	.18	.16	.08	.14
Al_2O_3	17.7	17.3	17.1	17.9	18.3	16.7	17.3	17.7	16.4	15.2	16.5	16.5	16.7	15.6	16.5	15.6	14.8	16.1
Fe_2O_3	.9	1.0	.9	.8	.7	.9	1.0	.6	.4	.3	.3	.7	.6	.2	.4	.1	1.2	.1
FeO	2.5	2.2	2.3	2.3	1.8	2.1	1.9	2.2	1.6	1.4	1.4	1.5	1.9	1.5	1.4	1.2		1.3
MgO	1.2	1.1	1.2	1.1	.8	.8	1.0	.9	.6	.5	.6	.7	.7	.4	.5	.4	.2	.3
CaO	4.1	3.9	4.1	4.2	3.9	3.6	3.8	4.0	2.5	2.2	2.3	2.2	2.8	2.3	2.1	1.8	1.0	1.6
Na_2O	3.4	3.4	3.2	3.3	3.6	3.3	3.4	3.5	3.6	3.5	3.3	3.3	3.5	3.5	3.5	3.8	4.1	3.2
K_2O	3.7	3.2	3.3	3.1	3.4	3.3	3.7	3.3	3.5	3.5	4.2	3.8	3.3	3.5	4.3	3.4	4.2	3.9
Total		100.53		100.29		100.18		99.61		99.75		99.61		99.48		99.56		99.84
	100.32		100.09		100.67		99.64		100.01		101.60		99.54		101.38		100.88	

* The ferrous iron determination for sample Y is suspect so all iron in this sample is reported as ferric iron.

Table 2 -- Continued

Southern Mount Powell batholith*

Sample	AA	BB	CC	DD	EE	FF	GG
SiO_2	72.2	72.3	72.7	72.0	74.6	72.8	68.8
TiO_2	.19	.16	.18	.18	.09	.20	.20
Al_2O_3	16.1	16.0	15.8	16.3	14.6	15.8	18.2
Fe_2O_3	1.9	1.4	1.9	1.7	1.0	2.4	2.5
MgO	.6	.4	.5	.5	.2	.6	.6
CaO	2.3	2.1	1.9	2.0	2.0	2.6	3.6
Na_2O	3.4	3.9	3.4	3.9	3.4	3.3	4.0
K_2O	3.5	3.7	3.4	3.4	3.3	3.1	2.6
Total	100.19	99.96	99.78	99.98	99.19	100.80	100.50

*Ferrous iron was not determined for these samples so the Fe_2O_3 values represent total iron.

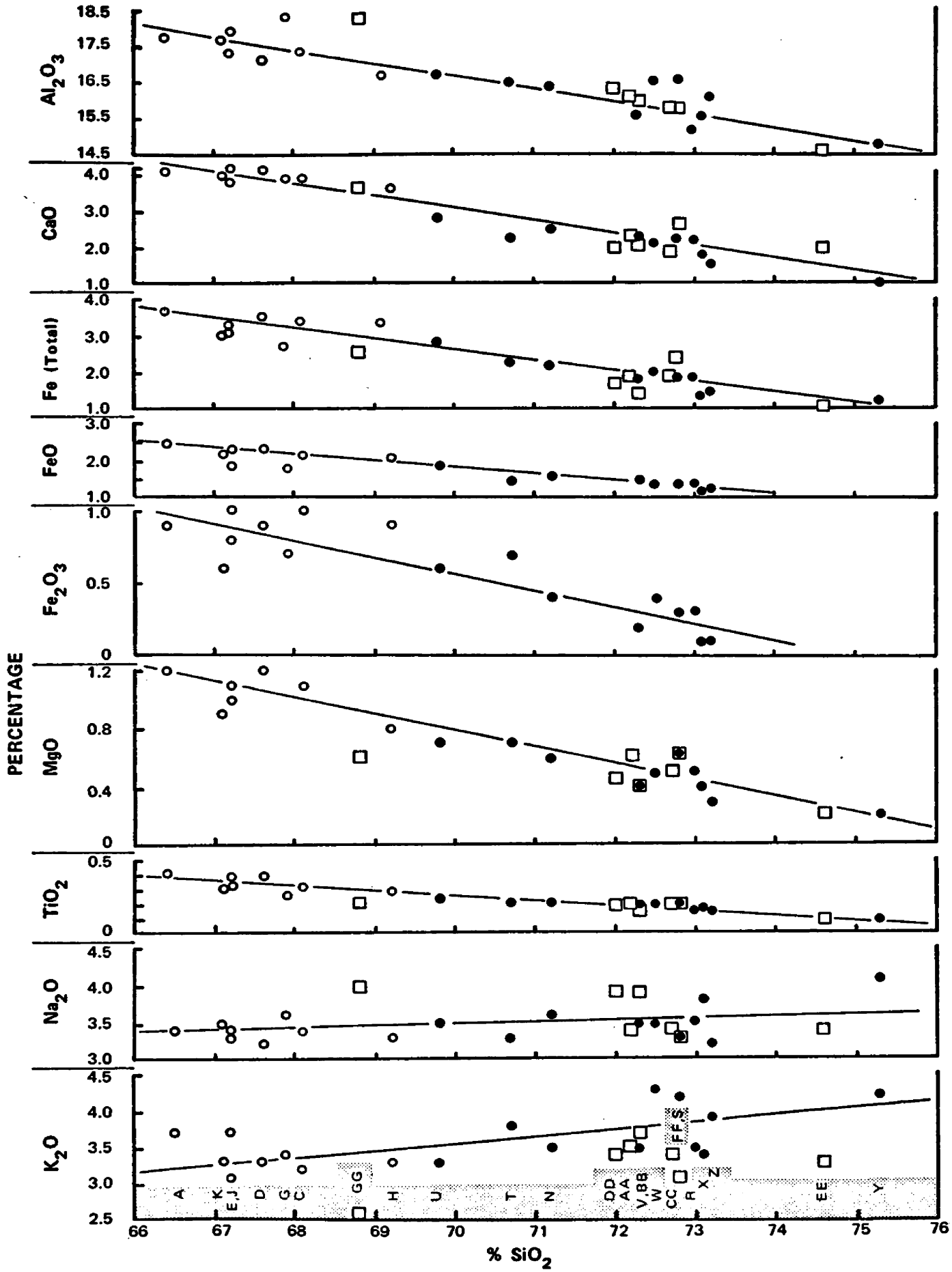


Figure 8. Variation diagram for samples from the Royal stock and Mount Powell batholith. Open circles represent Royal stock samples, closed circles represent the northern Mount Powell samples, and squares represent southern Mount Powell samples.

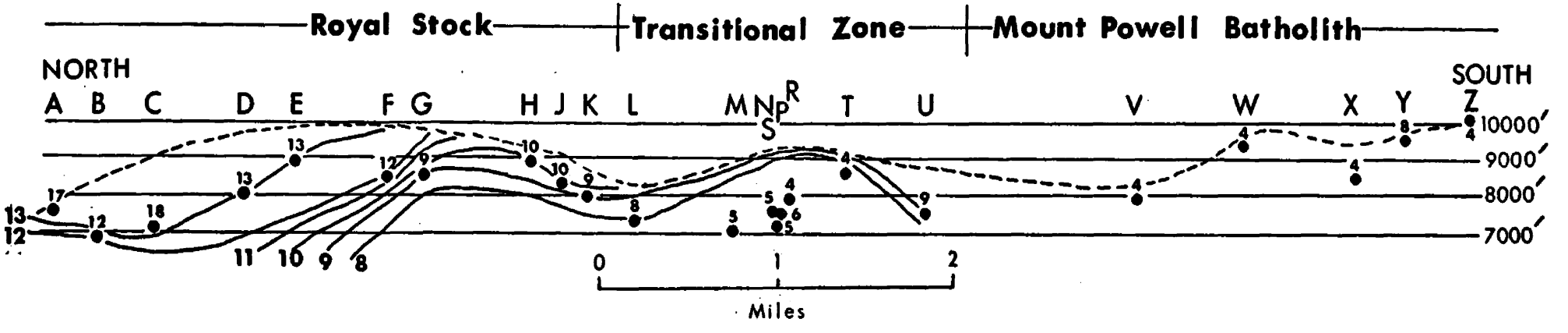


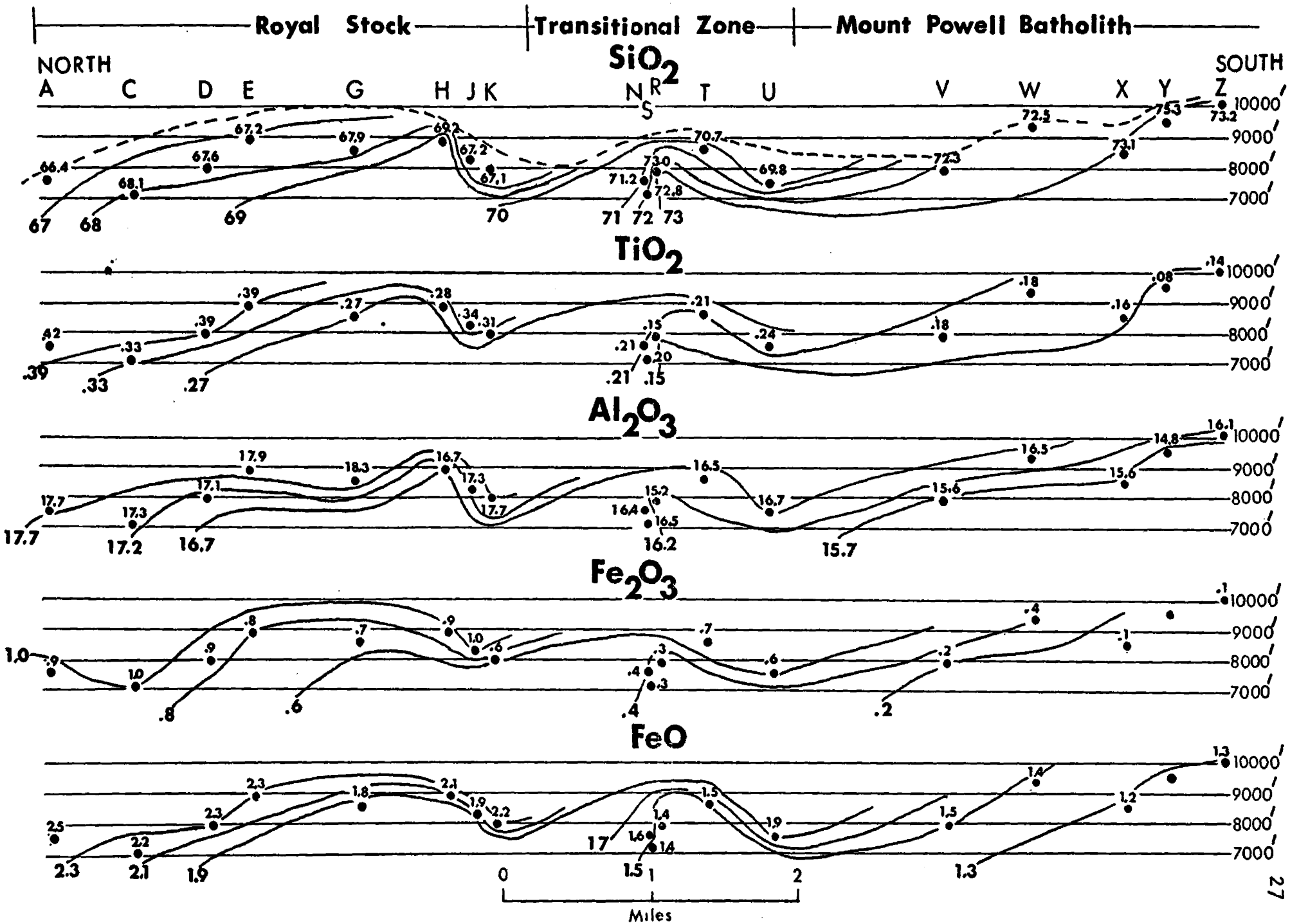
Figure 9. Contoured cross-sectional plot of magnetic susceptibility measurements. Dashed line is the estimated position of the original roof of the plutons. Note similarities in contour shape between this figure and Figures 10 and 13. Units for the numbers shown are x 10^{-4} C.G.S. units.

Samples Y and EE fall close to trends defined by the other samples (Fig. 8) but have more silica and less mafic constituents. These samples probably represent further local differentiation of the Mount Powell batholith.

Analyses of the whole rock major oxides clearly show vertical compositional variation in the Royal stock (Fig. 10). This zoning agrees with the density variation of the Royal stock as more mafic material is found near the margins and higher elevations (Fig. 6). This zoning is generally parallel to the inferred roof. No mineralogical zoning was detected, presumably because the range of chemical variation is not large enough to cause sufficient variation in the mineralogy of the Royal stock to be detectable outside of the analytical error. The cross section showing K_2O contents (Fig. 10) suggests that samples A and J may most nearly represent the original potassium content of the magma. Below the shell defined by these two values there appears to be a zone from which potassium was selectively removed.

Zoning similar to that exhibited in the Royal stock, although less clearly defined, is present in the northern part of the Mount Powell batholith where the gradational transition between the two plutons is believed to occur (Fig. 10). Allen (1962) has suggested that in this transitional zone near East Goat Mountain the Mount Powell batholith has intruded the Royal stock and structurally domed it to the east and west. It is believed that the Mount Powell batholith broke through the Royal stock in this area.

It is not possible to prove if vertical zoning is present in the southern part of the Mount Powell batholith as only seven chemical analyses were performed on widely scattered rocks. The correlations of density (increasing density with increasing elevation in the northern part of the


Royal Stock
Transitional Zone
Mount Powell Batholith
NORTH
SOUTH
A C D E G H J K N R S T U V W X Y Z
SiO2
TiO2
Al2O3
Fe2O3
FeO
10000
9000
8000
7000
0 1 2
Miles

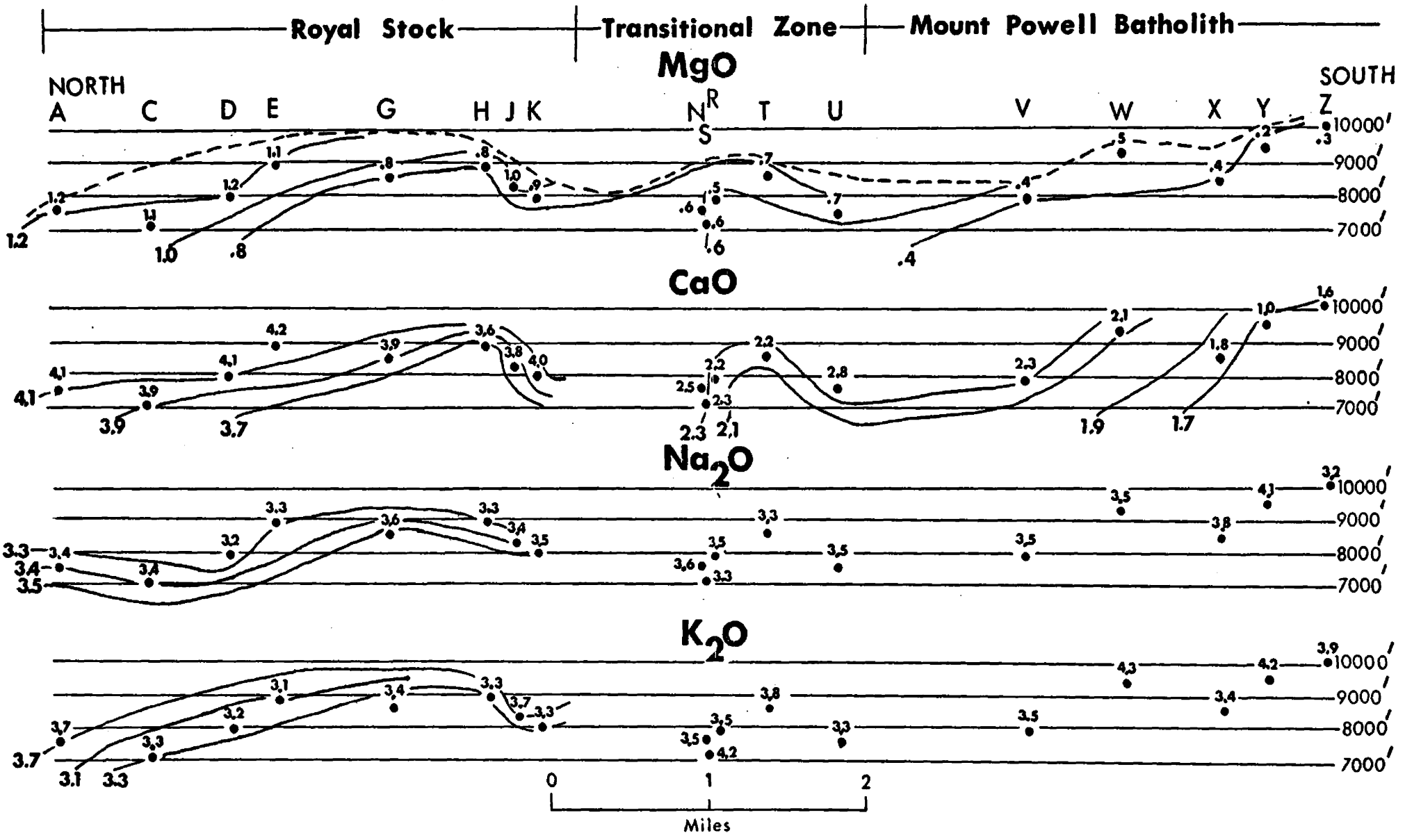


Figure 10. Cross-sectional plot of whole rock oxides along line of samples shown in Figure 2. Note similar vertical zoning for all oxides in the Royal stock and the gradational relationship between the Royal stock and Mount Powell batholith. No contours were drawn for Na_2O and K_2O in the Transitional zone and the Mount Powell batholith due to variations probably caused by potassium feldspar megacrysts. Dashed line in the SiO_2 and MgO plots is the estimated position of the roof of the plutons.

Mount Powell batholith and increasing density with decreasing elevation in the southern portion, particularly deep in the Racetrack Creek Valley) with elevation in the Mount Powell batholith suggests vertical compositional zoning may also be present in this body. This weaker zoning shown by the Mount Powell batholith is compatable with the proposed origin. The closer a granitic magma approaches its minimum melt composition, the more difficult it is for that magma to undergo further changes in composition. The Mount Powell batholith should show smaller changes in composition than the Royal stock because when emplaced it was at a more advanced stage of differentiation than the Royal stock.

Assimilation of mafic country rock has been invoked by some workers as an explanation of the origin of concentric compositional zoning in some granitic plutons (Compton, 1955; Reesor, 1958). However, there are several lines of evidence which suggest assimilation of country rock is not responsible for the chemical variation observed in the Royal stock and Mount Powell batholith.

1. Xenoliths are very rare in the Royal stock and completely absent in the Mount Powell batholith.

2. Both plutons have a homogeneous igneous texture (hypidiomorphic-granular) which implies that if any large quantity of relatively mafic country rock was assimilated, it was completely fused and dispersed into the surrounding magma. Total melting and dispersion of relatively mafic material in a granitic magma is subject to formidable thermal problems not encountered by in place differentiation.

3. Country rock in contact with the Royal stock and Mount Powell batholith ranges from quartzite to limestone in composition (Allen, 1962). Assimilation of such chemically diverse rocks would not tend to produce

bodies as mineralogically homogeneous as the Royal stock and Mount Powell batholith.

4. The outer portions of the Royal stock being enriched in K_2O relative to the interior portions is not explainable by assimilation of more mafic country rock.

Chapter 7

BIOTITE CHEMISTRY

Sample Preparation

Biotites from the <40 but > 80 mesh size split of the ground whole rock were initially concentrated with a Franz isodynamic separator. The concentrates were then crushed, but not ground, by vertical pounding of a pestle in a large porcelain mortar. This shattered any inclusions and compound grains present but didn't appreciably reduce the size of the biotite flakes. The samples were then ultrasonically vibrated in distilled water for several minutes to shake loose any extraneous material and separate the individual biotite grains which tended to form clusters after the crushing procedure. The samples were then dried and sieved, with the >115 mesh portion being further concentrated by repeated passes through the Franz isodynamic separator. Heavy liquids were not needed and hand picking was necessary only for samples Y and Z, which appeared to be partly altered under the microscope. Final sample purity from microscopic visual estimates is believed to be 99% or better, although a few inclusions of apatite or muscovite and some compound grains were still present.

Occurrence of Biotite and Muscovite

Biotite is the only primary ferromagnesian silicate present in the Royal stock and Mount Powell batholith. The good correlation between the amount of biotite present and the MgO content of the whole rock (Fig. 11) suggests the availability of magnesium was the limiting factor in biotite

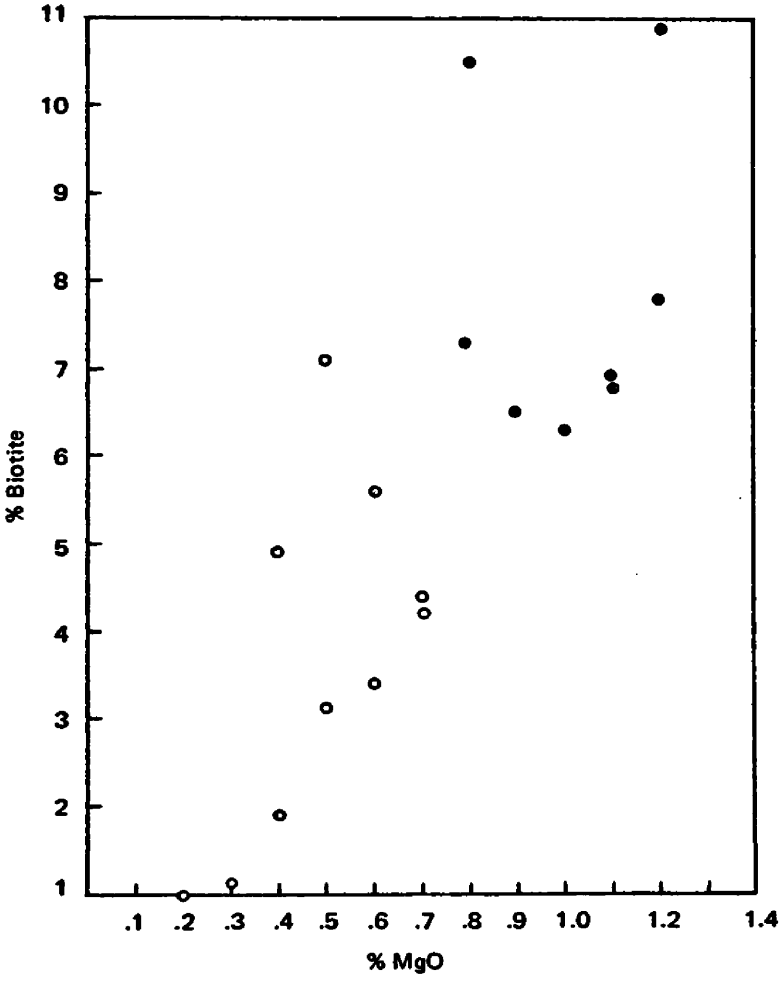


Figure 11. Relation between abundance of biotite and magnesium content of host rock. Solid circles represent Royal stock samples and open circles represent Mount Powell samples.

formation. Iron, silica, potassium, and aluminum are present in excess of the amount required for biotite formation and appear as quartz, magnetite, and late-stage potassium feldspar and muscovite respectively. Biotite is much more prevalent than muscovite in the Royal stock, whereas both are present in subequal amounts in the Mount Powell batholith (Table 1).

In all muscovite-bearing samples biotite and muscovite are closely associated. Muscovite cuts across biotite grains at high or low angles, truncates or interfingers with the ends of some books, or partially rims or appears as inclusions in the biotite.

Much of the muscovite in the Royal stock appears to be secondary, as it is fine-grained, in many cases interstitial, and has a "ratty" appearance. The opposite can be said for most of the muscovite in the Mount Powell batholith. This muscovite may, on the basis of textural evidence, be either primary (i.e. crystallized from a silicate melt) or be the product of deuteric alteration. It seems reasonable that deuteric processes acting over a long period of time and in the presence of abundant fluids could produce muscovite which looks primary. It has been suggested that primary magmatic muscovite may form only in deep seated granitic rocks (eg:Hyndman, 1972). As these plutons are epizonal and myrmekite, which may also be a late stage replacement phenomenon, is present, it is believed that all the muscovite is of deuteric origin.

The presence of more and larger muscovite crystals in the Mount Powell batholith than in the Royal stock agrees well with the proposed separation of a more differentiated, and presumably more fluid-rich magma from its earlier-crystallized shell. The fluid-rich nature of the magma would inhibit nucleation of crystals and aid crystal growth by allowing further and faster diffusion of ions to the growing crystals (eg:Hyndman, 1972).

The biotite is generally evenly disseminated throughout the rock (excluding megacrysts), although it may impart a foliation near the borders of the Royal stock. The habit ranges from moderately thin plates to moderately thick books. Biotites from all samples have the same habits. Most grains are fresh, but interlamination with chlorite or alteration of the edges of crystals to chlorite and epidote is also present. Common inclusions in the biotite are zircon, magnetite, apatite, and muscovite.

Optical Properties of the Biotites

The most prevalent biotite in all samples has the pleochroic scheme X = light yellow and Y = Z = dark brown with X < Y = Z. In samples M, R, and S which are located in the contact zone between the two plutons, a second biotite has the pleochroic scheme X = light yellow and Y = Z = dark green with X < Y = Z. This second biotite is always found in close association with muscovite from which it may be growing, however, one grain was gradational into a normal biotite. This green biotite is present in very minor quantities in samples M and R, but in sample S it forms about 5% of the total biotite. As the chemical analysis for sample S (Table 3) is very similar to other nearby samples and the green biotite was probably separated with the muscovite, it is believed this second biotite has no effect on the chemical analysis.

Refractive indices $\frac{1}{2}(\beta+\gamma)$ for all the biotites are very similar, falling in the range 1.642 to 1.648. The estimated error of $\pm$ .002 in the determinations makes this data unsuitable for determining trends. Optic axial angles of all samples are very similar and less than 15°.

Composition of the Biotites

Chemical analyses of biotites (Table 3) were performed in the same manner as the whole rock analyses. Structural formulae were calculated

Table 3. Biotite analyses

Sample		A		B		C		D		E		F		G		H	
Chemical analyses																	
SiO_2		38.2		38.3		38.0		38.1		38.1		37.9		37.3		37.3	
TiO_2		2.74		2.83		2.73		2.96		2.81		2.83		2.79		2.78	
Al_2O_3		17.8		18.8		18.5		18.6		18.0		18.8		18.8		18.6	
Fe_2O_3		3.0		2.7		2.4		2.7		3.1		3.5		2.8		2.1	
FeO		15.7		16.3		16.8		16.7		15.6		15.4		17.1		17.2	
MgO		12.1		11.8		11.5		11.1		12.1		11.4		10.8		10.7	
CaO		.3		.5		.3		.5		.3		.6		.5		.4	
Na_2O		.1		.1		.1		.1		.1		.1		.1		.1	
K_2O		9.2		9.1		9.6		9.5		9.7		9.5		8.9		9.5	
Total		99.14		100.43		99.93		100.26		99.81		100.03		99.09		98.68	
Structural formulae																	
Si	Z	2.75	4.00	2.72	4.00	2.73	4.00	2.73	4.00	2.73	4.00	2.71	4.00	2.70	4.00	2.72	4.00
Al		1.25		1.28		1.27		1.27		1.27		1.29		1.30		1.28	
Al^{+++}	Y	.26	2.81	.29	2.80	.30	2.82	.30	2.79	.25	2.79	.29	2.76	.30	2.80	.32	2.80
Fe^{+++}		.16		.14		.13		.15		.17		.19		.15		.12	
Ti		.15		.15		.15		.16		.15		.15		.15		.15	
Mg^{++}		1.30		1.25		1.23		1.18		1.29		1.21		1.17		1.16	
Fe^{++}		.94		.97		1.01		1.00		.93		.92		1.03		1.05	
Ca	X	.02	.87	.04	.88	.02	.91	.04	.92	.02	.92	.05	.93	.04	.87	.03	.92
Na		.01		.01		.01		.01		.01		.01		.01		.01	
K		.84		.83		.88		.87		.89		.87		.82		.88	
Atomic ratios																	
Fe^{+++}		6.7		5.9		5.5		6.4		7.1		8.2		6.4		5.1	
Fe^{++}		39.2		41.4		42.6		42.9		38.9		39.7		43.8		44.9	
Mg		54.1		53.0		51.9		50.6		54.0		52.1		49.8		50.0	
Fe/(Fe+Mg)		45.9		47.3		48.1		49.3		46.0		47.9		50.2		50.0	

Table 3. --Continued

Sample		J		K		L		M		N		P		R		S	
Chemical analyses																	
SiO_2		37.5		37.7		37.1		37.2		37.4		37.8		37.2		37.8	
TiO_2		2.82		2.85		3.01		2.77		2.67		2.73		2.67		2.74	
Al_2O_3		18.0		19.2		18.5		18.2		19.0		19.4		19.0		18.7	
Fe_2O_3		2.8		2.8		3.1		2.2		2.1		2.2		2.2		2.9	
FeO		16.9		17.2		17.9		18.2		17.9		18.4		18.4		17.8	
MgO		11.4		11.2		10.0		10.9		10.6		10.5		10.4		10.4	
CaO		.7		.9		.3		.4		.3		.4		.4		.2	
Na_2O		.1		.1		.1		.1		.1		.1		.1		.1	
K_2O		9.7		9.4		9.3		9.0		9.0		9.3		9.2		9.6	
Total		99.92		101.35		99.31		98.97		99.07		100.83		99.57		100.24	
Structural formulae																	
Si	Z	2.71	4.00	2.68	4.00	2.70	4.00	2.71	4.00	2.71	4.00	2.70	4.00	2.70	4.00	2.72	4.00
Al	Z	1.29		1.32		1.30		1.29		1.29		1.30		1.30		1.28	
Al^{+++}	Y	.24	2.79	.28	2.78	.29	2.79	.27	2.83	.33	2.81	.33	2.82	.32	2.82	.31	2.81
Fe^{+++}	Y	.15		.15		.17		.12		.11		.12		.12		.16	
Ti	Y	.15		.15		.16		.15		.15		.15		.15		.15	
Mg^{++}	Y	1.23		1.18		1.08		1.18		1.14		1.12		1.12		1.12	
Fe^{++}	Y	1.02		1.02		1.09		1.11		1.08		1.10		1.11		1.07	
Ca	X	.05	.95	.07	.93	.02	.89	.03	.88	.02	.86	.03	.89	.03	.89	.02	.91
Na	X	.01		.01		.01		.01		.01		.01		.01		.01	
K	X	.89		.85		.86		.84		.83		.85		.85		.88	
Atomic ratios																	
Fe^{+++}		6.2		6.4		7.3		5.0		4.7		5.1		5.1		6.8	
Fe^{++}		42.5		43.4		46.6		46.1		46.4		47.0		47.2		45.5	
Mg		51.3		50.2		46.1		48.9		48.9		47.9		47.7		47.7	
Fe/(Fe+Mg)		48.7		49.8		53.9		51.1		51.1		52.1		52.3		52.3	

Table 3. --Continued

Sample	T		U		V		W		X		Y		Z	
Chemical analyses														
SiO_2	36.9		37.3		38.0		37.3		37.7		37.6		38.1	
TiO_2	2.74		2.67		2.73		2.78		2.66		2.55		2.68	
Al_2O_3	18.6		18.5		18.5		18.8		18.9		18.8		18.4	
Fe_2O_3	2.9		2.3		2.6		2.5		3.0		4.9		2.3	
FeO	18.1		18.0		17.8		17.6		18.0		17.8		18.4	
MgO	10.0		10.3		9.9		10.0		9.7		9.8		9.5	
CaO	.2		.3		.2		.3		.4		.6		.6	
Na_2O	.1		.1		.1		.1		.1		.1		.1	
K_2O	9.8		9.8		9.7		9.7		9.2		7.1		8.5	
Total	99.34		99.27		99.53		99.08		99.66		99.25		98.58	
Structural formulae														
Si (Z)	2.70	4.00	2.72	4.00	2.75	4.00	2.72	4.00	2.73	4.00	2.71	4.00	2.77	4.00
Al (Z)	1.30		1.28		1.25		1.28		1.27		1.29		1.23	
Al^{+++} (Y)	.30		.31		.33		.33		.34		.31		.35	
Fe^{+++} (Y)	.16		.13		.14		.14		.16		.27		.13	
Ti (Y)	.15	2.80	.15	2.81	.15	2.77	.15	2.77	.15	2.78	.14	2.84	.15	2.78
Mg^{++} (Y)	1.09		1.12		1.07		1.08		1.04		1.05		1.03	
Fe^{++} (Y)	1.10		1.10		1.08		1.07		1.09		1.07		1.12	
Ca (X)	.02		.02		.02		.02		.03		.05		.05	
Na (X)	.01	.94	.01	.94	.01	.93	.01	.93	.01	.89	.01	.71	.01	.85
K (X)	.91		.91		.90		.90		.85		.65		.79	
Atomic ratios														
Fe^{+++}	6.8		5.5		6.1		6.1		7.0		11.3		5.7	
Fe^{++}	46.8		46.8		47.2		46.7		47.6		44.8		49.1	
Mg	46.4		47.7		46.7		47.2		45.4		43.9		45.2	
Fe/(Fe+Mg)	53.6		52.3		53.3		52.8		54.6		56.1		54.8	

(Table 3) based on a unit cell of eleven oxygens with water not considered.

The large twelve-coordinated cations, Ca, Na, K, of the X group range from .85 to .95 with the exception of sample Y which is partially weathered. The X group cations supply charges ranging from .88 to 1.00. Na is constant at .01, Ca ranges from .02 to .07, and K varies from .79 to .91 with most values ranging from .83 to .91.

The Y group cations Fe^{++}, Fe^{+++}, Mg, Ti, and Al, occupy from 2.76 to 2.83 of an ideal 3.00 octahedral sites. Of these elements only Ti remains constant at .15. The greatest variation is shown by Fe^{++} and Mg which range from .92 to 1.12 and from 1.03 to 1.30 respectively. Excluding sample Y, Fe^{+++} varies randomly from .11 to .19 and Al ranges from .24 to .35.

The tetrahedrally coordinated Z group of elements consists entirely of Si and Al with Si varying from 2.68 to 2.75 and Al ranging from 1.23 to 1.32. Presumably all four sites are filled.

With the exception of iron and magnesium contents, all the biotites are very similar.

Petrogenesis of Biotites

Experimental work by Wones and Eugster (1965) demonstrates the effect of oxygen fugacity on the synthesis and resultant composition of biotites on the phlogopite-annite join. If it is assumed that substitutions other than Fe $\leftrightarrows$ Mg will not greatly influence biotite stability, application of the experimental data of Wones and Eugster (1965) to biotites from the Royal stock and Mount Powell batholith may permit an evaluation of the oxygen fugacities and temperatures during crystallization of these plutons.

When plotted on the compositional triangle Fe^{+++}-Fe^{++}-Mg (Fig. 12) the data appear ambiguous as to whether the oxygen fugacities followed a "buffer curve" (Dodge, Smith, and Mays,1969), where the buffer remains

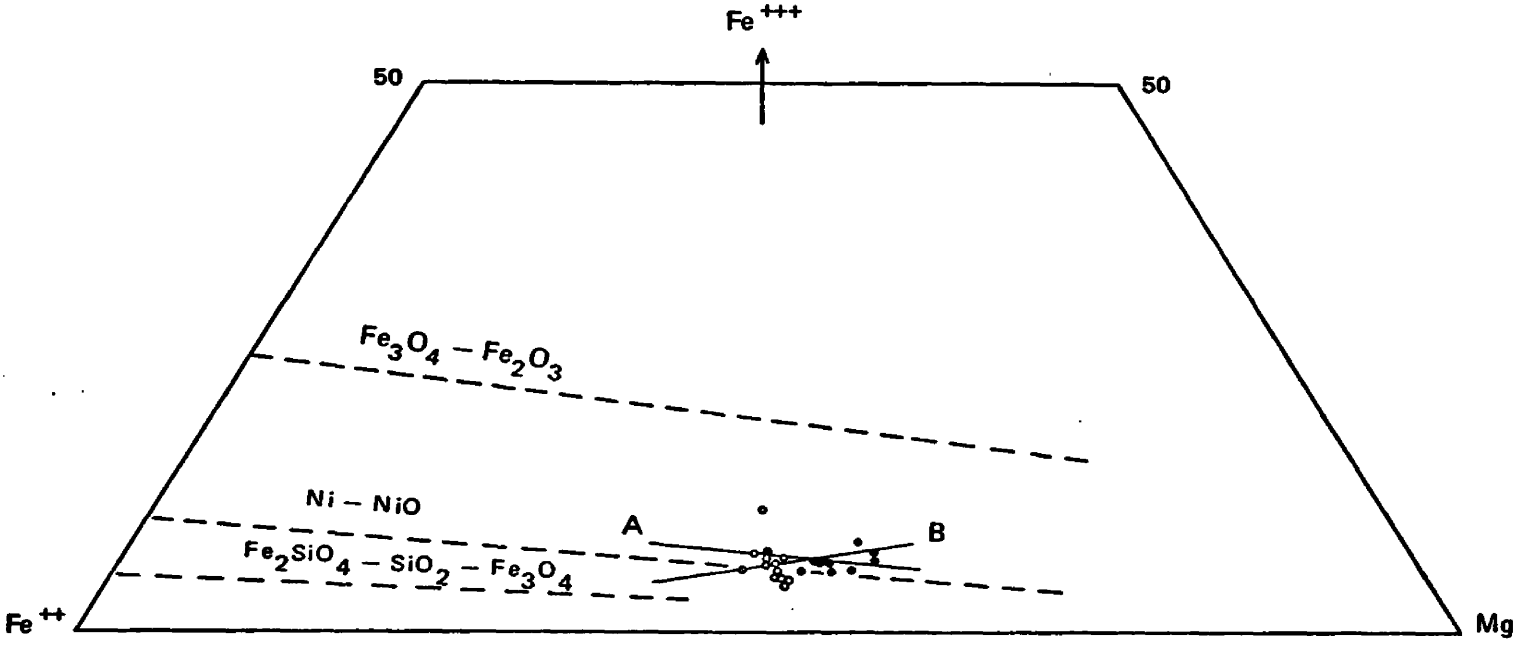


Figure 12. Relation of Fe^{+3} - Fe^{+2} - Mg contents of Royal stock and Mount Powell biotites. Dashed lines represent compositions of "buffered" biotites in the ternary system $KFe^{+3}_3AlSi_3O_{12}H_{-1}$ - $KFe^{+2}_3AlSi_3O_{10}(OH)_2$ - $KMg_3AlSi_3O_{10}(OH)_2$ depicted by Wones and Eugster (1965, Fig. 1). Open circles represent Mount Powell biotites and closed circles represent Royal stock biotites. Two possible trends are shown. The trend along line A is that of a "buffer curve" while the trend along line B is suggestive of a change in buffer.

constant and the associated f_{O_2} decreases with decreasing temperature, or the buffer changed slightly during crystallization. Other evidence, however, strongly suggests that the oxygen fugacities followed a "buffer curve" during crystallization:

1. All biotites coexist with potassium feldspar and magnetite. The four phases, biotite, potassium feldspar, magnetite, and melt(which contains water),act as f_{O_2} buffers (Wones and Eugster, 1965).

2. Changes in the silicate mineralogy agree with the oxygen fugacities following a "buffer curve". The Mount Powell batholith is enriched in quartz, potassium feldspar, and the sodic component of plagioclase relative to the Royal stock and presumably crystallized at lower temperatures. Biotites from the Mount Powell batholith are more iron-rich than those from the Royal stock (Table 3).

If the oxygen fugacities followed a "buffer curve" as suggested by the previous evidence, then the temperature variations will be reflected in the biotite compositions. More iron-rich biotites will be crystallized as f_{O_2} decreases with decreasing temperature.

A cross-sectional plot of Fe/(Fe+Mg) ratios of the biotites along the line of samples (Fig. 13) shows contours of equal composition to be parallel to the inferred roof of the Royal stock. The lower Fe/(Fe+Mg) ratios nearest the margins of the Royal stock indicate that the margins crystallized at higher temperatures than the interior of the pluton. The more mafic margins of a pluton differentiating in place should crystallize at higher temperatures than the more differentiated interior. The contours of equal Fe/(Fe+Mg) ratios for the biotites from the northern part of the Mount Powell batholith show a general iron enrichment trend both toward the interior of the pluton and with increasing depth. The iron enrichment

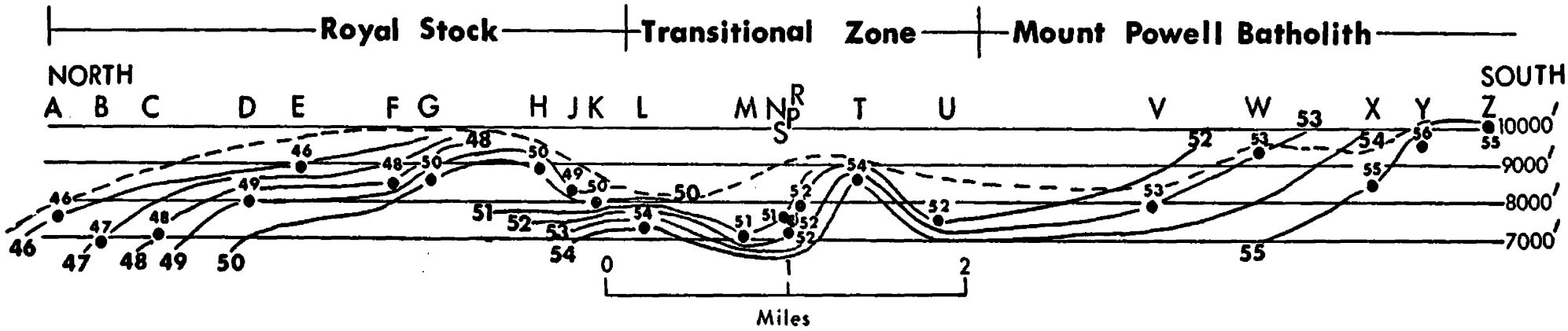


Figure 13. Contoured cross-sectional plot of Fe/(Fe+Mg) x 100 ratios of biotites interpreted as showing vertical thermal zoning. Dashed line is the estimated original position of the roof of both plutons. Note that the contours are generally parallel to the estimated roof.

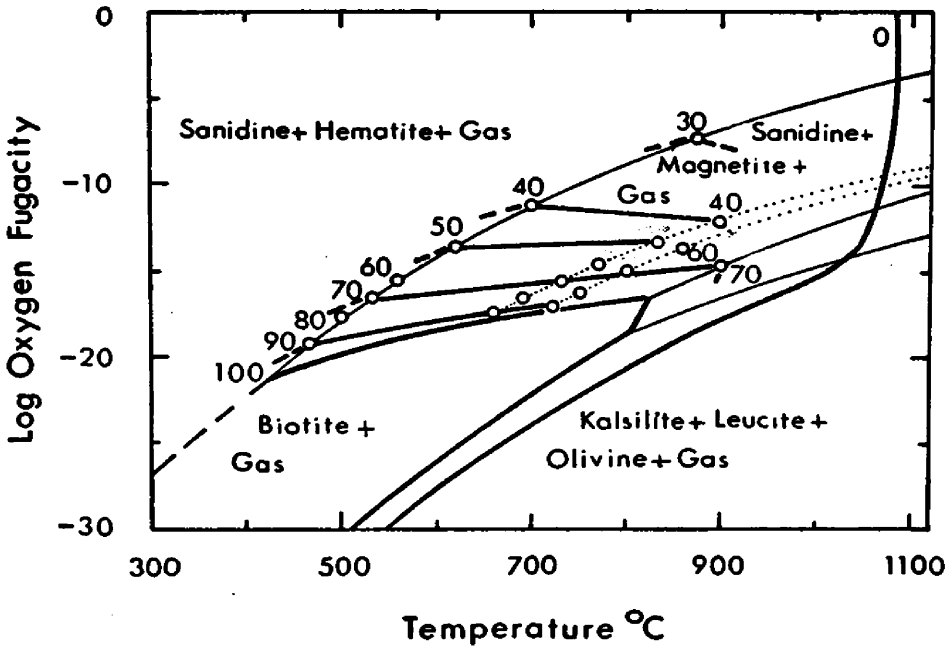


Figure 14. Stability of biotites of specific Fe/(Fe+Mg) values as a function of oxygen fugacity and temperature at 2070 bars total pressure. Heavy lines represent contours of constant 100 x Fe/(Fe+Mg) values. Lightweight lines and dotted lines depict buffer curves. Diagram from Wones and Eugster (1965, Fig. 4).

Although the thermodynamic parameters are different between the Ni-NiO buffer and the buffering compounds in the magma it is believed the slopes are similar because ΔS^{o} is probably positive for all buffers. This is reasonable as the entropy change is primarily due to oxygen release. Therefore, the shaded area represents the F_{O_2} and temperature trends of the crystallizing magma.

trends suggest that both plutons were undersaturated with respect to water.

A maximum temperature range of 50° C in temperature of crystallization of biotites between the Royal stock and Mount Powell batholith is suggested (Fig. 14). The predicted oxygen fugacities are slightly, with the exception of sample Y, above those defined by the Ni - NiO buffer (Fig. 12).

Correlation between Fe/(Fe+Mg), an inferred temperature indicator, and other elements is generally poor, with the exception of octahedral Al which increases with increasing Fe/(Fe+Mg). This trend has also been noted by Dodge, Smith and Mays (1969).

The biotite data are in agreement with the proposed origin of both plutons. The temperature-indicating Fe/(Fe+Mg) ratios suggest that a vertical thermal zonation was present in the Royal stock during crystallization. The Fe/(Fe+Mg) ratios also suggest temperatures of biotite crystallization gradationally decrease from the Royal stock into the Mount Powell batholith. As expected, inferred temperatures of biotite crystallization are gradational between the margins of a pluton and its partially separated core.

Chapter 8

CONCLUSIONS

Structural, density, and whole rock chemical data suggest that the Royal stock represents the top of a vertically zoned pluton which has differentiated in place. Biotite chemistry suggests that the Royal stock magma was buffered with respect to the oxygen fugacity and cooled from the margins inward, with higher temperatures of crystallization nearest the margins. The solidified margins of the Royal stock probably formed an impervious shell which sealed in volatiles and allowed differentiation in place to progress. There is no evidence to suggest that the zoning in the Royal stock was caused by assimilation of country rock.

Gradational whole rock and biotite chemistry, along with similar mineralogies, suggest there is a close genetic relationship between the Royal stock and Mount Powell batholith. The Mount Powell batholith is interpreted as being the more differentiated deeper portion of the Royal stock magma which, possibly due to gravitational instability, broke through the solidified southern side of the Royal stock and was emplaced as a separate pluton. It is suggested that the Mount Powell batholith may be sheet-like in form and only one or two miles thick.

APPENDIX I

MODAL ANALYSES

Both unstained thin sections and sawn slabs stained with sodium cobaltinitrite were point counted with a mechanical stage. The slabs were stained according to the technique used by Ehinger (1971).

Random traverses with a distance of 0.33 mm between points were made across the stained slabs until 2000 counts were made. The large alkali feldspar megacrysts in the Mount Powell batholith made some slabs unsuitable for counting. It is believed that the modal analyses from the Mount Powell batholith are only useful for qualitative deductions. The more homogeneous slabs of the Royal stock are much better suited for modal analyses and it is believed the results are fairly reliable.

Thin section point counts, believed to be more accurate for relative biotite and muscovite contents, were done using regularly spaced traverses across a thin section with a distance of 0.1 mm between points. A total of 1440 counts were made for each thin section.

APPENDIX II

CHEMICAL ANALYSES

General Sample Preparation

Rock samples were crushed in a chipmunk crusher and then ground to finer size in a disc grinder. Whole rock splits were then removed and the remainder of the rock sieved into size fractions of >42, <42 and >80, and <80 mesh. The whole rock splits were used for whole rock chemical analyses and magnetic susceptibility measurements. For chemical analyses the whole rock splits were repeatedly split with a sample splitter until the desired amount of sample was present. This portion was then ground in a tungsten carbide ball mill for approximately one minute. Any iron contamination introduced by crushing and grinding could not be removed due to the presence of magnetite. The biotites were separated from the <40 and >80 mesh fractions.

Ferrous Iron Determinations

Ground whole rock samples and pure biotite splits were dried overnight at 100° C and then enough sample to contain 15 to 20 mg of FeO was placed in a polypropylene bottle. A carefully measured volume (usually 20 ml) of a NH_4VO_3 solution, prepared by dissolving 3.256 g of NH_4VO_3 in a solution of 125 ml distilled water and 25 ml of conc. H_2SO_4 and then diluting to 1000 ml, was added to the bottle. Next 20 ml of 1:3 H_2SO_4 and 5 to 10 ml of 48% HF were added and the bottles were capped and placed in an oven at 90° C overnight. The next day 10 ml of 1:3 H_3PO_4 and 5 drops of sodium diphenylammine-sulfonate indicator solution, prepared by dissolving 0.1 g of sodium diphenylammine-sulfonate in 10 ml of conc. H_2SO_4, were

added. The sample was then titrated with a Fe^{++} solution prepared by dissolving 12.0 g of $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$ in a solution of 500 ml of distilled water and 10 ml of conc. H_2SO_4 and diluting to 1000 ml. The wt. % FeO was calculated using the following formulae:

Standardization Factor = F

$$F = \frac{\text{ml of } NH_4VO_3 \text{ used in the blank solution}}{\text{ml of } Fe^{++} \text{ used in the blank solution}}$$

$$\text{Wt. \% FeO} = \frac{(\text{ml } NH_4VO_3) - (\text{ml } Fe^{++})\ (F) \times 200}{\text{sample wt in mg}}$$

At least two titrations were performed on each sample and two blanks, from which the standardization factor is calculated, were run with each batch of samples.

It is believed the FeO contents of the whole rock are accurate to $\pm$ 0.1% and the FeO contents of the biotites are accurate to $\pm$ 0.2% of the total.

Sodium and Potassium Analyses Using the Flame Photometer

The biotite and ground whole rock samples were heated for 3 hours at 1050° C to oxidize all ferrous iron and drive off all the water present. As several days passed between oxidation and dissolution all samples were dried overnight at 100° C before dissolution. Enough sample to produce a several part per million (ppm) solution when diluted to the desired volume was weighed out into a platinum crucible and dissolved in a heated mixture of conc. HF and $HClO_4$, the exact proportions of which varied considerably from sample to sample. This solution was evaporated to dryness and the residue redissolved in heated conc. $HClO_4$ and then diluted to 100 ml if the sample was a biotite or to 250 ml if the sample was a whole rock.

Several standards ranging from 0 to 10 ppm were prepared from a stock solution and used to define a working curve. USGS standards (G-2

and GSP-1), blanks and replicate samples were run with each batch of samples and suggest the accuracy of the sodium determinations to be ± 0.1%. Four potassium analyses were performed on the flame photometer as a check on the values obtained by x-ray fluorescence methods. Agreement was generally good to ± 0.1% or better of the total.

The Wt% Na is calculated by the equation

$$\text{Wt\% Na} = \frac{(\text{ppm Na})\ (\text{ml of sample})}{(10^6)\ (\text{sample wt})}$$

X-Ray Fluorescence Analyses

Ground and oxidized whole rock and biotite samples were diluted 1:2 and 1:3 respectively with lithium tetraborate and fused in carbon crucibles for 1/2 hour at 1050° C. The glass bead was then allowed to cool, crushed in a diamond mortar, ground in a tungsten carbide ball mill, and finally ground under alcohol or acetone in an agate mortar and pestle. The resulting powder was then pressed into a pellet with a boric acid backing. USGS standards G-2 and GSP-1 and a biotite standard supplied by Dr. U. Stern of the Institute of Mineralogy and Petrology at Basle, Switzerland were prepared with the samples in an identical manner.

The samples were analyzed on a Norelco x-ray vacuum spectrograph with a high intensity close-coupled chromium x-ray tube. Ca, Ti, and total Fe were analyzed without the vacuum whereas K, Si, Al, and Mg were analyzed under a vacuum. A pulse height distribution "window" was used for all elements except Fe and Ti for which only a 5 volt baselevel was used. A flow proportional counter was used for all analyses. All whole rock samples were analyzed against GSP-1 (Flannigan, 1967) and all the biotites were analyzed against the biotite standard supplied by Dr. U. Stern. Analyses of G-2 vs GSP-1 gave excellent results. The Fe_2O_3 content of both biotite and whole rock samples was obtained by subtracting the FeO content from the

total iron and is subject to errors in both analyses. As a consequence its precision is not as good as the other elements. All analyses were run through a modified computer program written by Hower and Schmittroth (1964) to correct for matrix effects.

The estimated precision of the analyses is shown in the table below:

	Whole rock	Biotite
$Fe_{(total)}$	± 0.1%	± 0.3%
Fe_2O_3	± 0.2%	± 0.5%
FeO	± 0.1%	± 0.2%
TiO_2	± 0.03%	± 0.05%
CaO	± 0.1%	± 0.0%
K_2O	± 0.1%	± 0.1%
SiO_2	± 0.5%	± 0.3%
Al_2O_3	± 0.3%	± 0.3%
MgO	± 0.1%	± 0.3%

These are percentages of the total amount--- not the amount present.

APPENDIX III

MAGNETIC SUSCEPTIBILITY

Magnetic susceptibility measurements were performed on a Bison Magnetic Susceptibility Meter, Model 3101. Ground whole rock samples were placed in plastic vials of known diameter and the susceptibility measured. Then the volume of air space in the sample was measured by filling all the air spaces with a measured volume of water. This allows the ratio of

$$\frac{\text{(true density of sample)}}{\text{(apparent density of sample)}}$$

to be calculated.

The magnetic susceptibility was then calculated by the formula

$$K_{(\text{mag. sus.})}\text{C.G.S. units} = C\Delta R \frac{1}{(\text{diameter}^2)} \frac{\text{(true density)}}{\text{(apparent density)}}$$

where C= calibration constant = 4.52×10^{-6}
R= dial reading
diameter = inside diameter of vial

APPENDIX IV

CORRELATION CHART

Sample Letter Used in Thesis	Number in University of Montana Collection
A	H31-12
B	S31-1
C	S31-3
D	S31-7
E	MP3-8
F	MP3-6
G	MP3-5
H	B8-7
J	B8-9
K	B8-10
L	B8-1
M	C1-1
N	C1-2
P	C1-5
R	C1-3
S	C2-2
T	B6-6
U	H4-13
V	S7-10
W	S7-7
X	H8-2
Y	H8-4
Z	H8-6
AA	H6-3
BB	MP2-1
CC	S19-2
DD	S6-3
EE	D4-4
FF	S9-9
GG	H16-2

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